THE STRUCTURE OF CHROMOSPHERES AROUND LATE-TYPE GIANTS AND SUPERGIANTS

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ABSTRACT

Observations α Tau (K5III) and β Gru (M2II) made at high resolution have been used to confirm line identifications of features blended at low resolution. The high resolution spectra allow selected pairs of lines to be used to find the electron density, N_e, and the opacity, τ. These can be used together with the emission measure to place constraints on the structure of the atmosphere. The line formation processes are briefly discussed. Photo-excitation by strong lines appears to be important in these late-type atmospheres.

INTRODUCTION

Previous observations made with the IUE satellite have shown that giants and supergiants later than about K2 do not have significant emission in lines which in the sun would be formed in the chromosphere-corona transition region (Refs 1-5). Instead, the observed spectra are dominated by lines formed at $T_e < 2 \times 10^4$ K. In particular strong OI resonance line emission is observed, which in the sun and α Boo has been shown (Ref. 6,7) to be produced via H Ly β excitation to a higher OI level.

High-resolution spectra have now been obtained of α Tau (K5III) and β Gru (M2II) in order to study line fluxes and profiles and also to confirm identifications of lines blended at low resolution. These spectra show that the strong OI lines themselves excite lines of SI (uv 9) (Ref. 8), and confirm the importance of SI as a contributor to other features in late-type stars, as noted previously for α Ori (M2 Ib) (Ref. 2). A line at 1641.2A is attributed to OI pumped by the OI resonance lines.

In this paper methods of determining the opacity, and electron density in addition to the usual emission measure are presented. The mechanisms by which particular emission lines are excited are briefly discussed.

OBSERVATIONS

The dates, exposure times and resolution of spectra used in the analyses are given in Table 1. All were obtained using the large slot. The observations were made at the ESA VILSPA Satellite Tracking Station with the assistance of the Resident Astronomers.

The low-resolution spectra and samples of the high-resolution spectra have been previously published (Refs. 1, 8) and are not illustrated here. The

GPHOT image provided by VILSPA is the basis of the further data reduction in which spectra can be summed and overexposed pixels removed. An algorithm provided by Gondhalekar was used to correct for the error in the original intensity transfer function for the SWP camera. The flux calibration used is that provided by Bohlin and Snijders (Ref. 9) and by Cassatella and Selvelli (Ref. 10).

METHODS OF ANALYSIS

The quantity usually derived from absolute line flux is the emission measure, $\int N_e^2\, dh$. For lines of neutral and singly ionized atoms the contribution function may be broad, and the region of formation not clearly defined. Also, below $T_e \sim 2 \times 10^4$ K, where hydrogen is not fully ionized, the relevant quantity is $\int N_e N_H\, dh$. Thus it is preferable to find $\int N_e N_H g(T)\, dh$, where g(T) is the temperature dependent part of the contribution function, as a function of temperature, and build up a self-consistent model by using several lines and independent determinations of N_e and τ ($\propto \int N_H\, dh$).

The electron density N_e may in late-type giants and supergiants be found from the relative intensity of lines within the $2s^2 2p^2\ {}^2P - 2s2p^3\ {}^4P$ multiplet of CII around 2325A. The transition probabilities have been calculated (Ref. 11) but cross-sections are available only by extrapolating data for OIV (Ref. 12) and NIII (Ref. 13). These approximate values lead to critical densities in the range 4×10^8 cm^{-3} to 6×10^7 cm^{-3}. With more accurate cross-sections the ratio of the CII multiplets at 1335Å and 2325Å may be used to determine T_e, providing collisional excitation is the dominant mechanism.

The opacity may be determined from the relative intensities of lines from a common upper level, where one of the lines is optically thin (Ref. 14). Using a simple probability of escape approach the ratio of the fluxes F, in two such lines is given by

$$F_1/F_2 = \lambda_2 b_1 q_1 / \lambda_1 b_2 q_2 \qquad (1)$$

where λ is the wavelength, b is the branching ratio, and q is the probability of escape, which is 1 for an optically thin line. Then since for a Gaussian line profile (Ref. 15),

$$q = 1 - \mathrm{erf}\left((\ln \tau_o)\ 1/2\right) \qquad (2)$$

where τ_o is the opacity at line centre, q and then τ_o can be found. The total opacity $\tau = 2\ \tau_o$ is given by

$$\tau = 1.2 \times 10^{-14}\ \lambda(A) f_{12} M^{1/2} \int \frac{N_E}{N_H} \frac{N_1}{N_{ion}} \frac{N_{ion}}{N_E} \frac{N_H}{T_i}{}^{1/2}\, ds \qquad (3)$$

where f_{12} is the absorption oscillator strength, M is the atomic weight, N_E, N_1, N_{ion} and N_H are the number densities of the element, lower level, ion (or atom) and hydrogen, respectively. T_i is the temperature corresponding to the Doppler width of the line. Although some approximations are necessary initially, the quantity $\int N_H\, ds$ can be determined, providing checks on models such as that by Kelch et al. (Ref. 16) for α Tau. Table 2 gives some examples of pairs of lines which can be useful. The method may also be applied to numerous lines of FeII above 2000Å. The oscillator strengths required for CI are given in Ref. 14; for OI values by Garstang (Ref. 17) have been used; for SI values are tabulated by Wiese et al. (Ref. 18).

It should be noted that the analysis of emission line fluxes and profiles in these late-type stars may be complicated by the long ionization and recombination times expected at $T_e < 2\times10^4$ K and densities of $<10^9$ cm^{-3}; times of 10^3-10^4s are estimated for neutral and singly ionized species.

RESULTS

The present paper emphasizes methods since further work on the atomic models and atomic data is required before quantitative analyses are possible. Some preliminary results are given below.

In α Tau the OI 1304/1641 ratio leads to $\int N_H\, ds \sim 8 \times 10^{21}$ cm^{-2}, and the CI 1657.4/1994 ratio to $\int N_H\, ds < 6 \times 10^{21}$ cm^{-2}, assuming all the population to be in the ground term. The SI lines at 1296.17Å and 1302.87Å have approximately the same intensity indicating $\tau > 1$ in these lines, and giving $\int N_H\, ds > 2 \times 10^{19}$ cm^{-2}. These values of 6-8×10^{21} are larger than expected from the model of the chromosphere of α Tau based on the MgII and CaII lines (Ref. 16). Also the absolute flux of the CII 2326Å line leads to an emission measure of $\sim 10^{28}$ cm^{-5} at 10^4K, again an order of magnitude larger than predicted. However, the CII 1335Å line is observed to be weaker than expected from CII 2325Å and improved excitation cross-sections are required before drawing definite conclusions regarding the temperature of formation. The SiII lines at 1808Å and 1817Å indicate other problems with the atomic model or cross-sections. They give an emission measure a further order of magnitude greater than found from CII 2326Å. It has been pointed out than in the sun the ^{2}D level can be excited predominantly from the metastable ^{4}P level rather than the ^{2}P level (Ref. 19). Cross-section calculations by Roberts (Ref. 20) supported this suggestion. However in α Tau and β Gru where $N_e<10^9$ cm^{-3}, the ^{4}P level does not acquire sufficient population for this explanation of the strength of ^{2}P-^{2}D to be appropriate. Either the cross-section for ^{2}P-^{2}D is still underestimated or other processes such as recombination or ionization are populating the metastable level. The absence of SiIII at 1892Å suggests however that the population of SiIII is low.

Simple estimates show that the OI emission in α Tau is too strong to be accounted for by collisional excitation or recombination but that the H Ly β excitation process could provide sufficient emission as in α Boo (Ref. 7).

Similar results are derived for β Gru. The opacity for OI is even larger, giving $\int N_H\, ds \sim 3\times10^{22}$cm^{-2}. The SI lines provide limits of $10^{19} < \int N_H\, ds < 4\times10^{22}$cm^{-2}. The CII 2325Å/1335 ratio again suggests a low

T_e or an overestimate of the 2325Å emission measure. The SiII 1808, 1817 lines require an emission measure an order of magnitude larger than that for CII 2325Å. For β Gru the CII $^2P-^4P$ line ratios can be used to determine N_e, giving a value of $\sim 10^8$ cm^{-3}.

The relative intensities of the FeII lines above 2000Å allow some general conclusions to be drawn. Although the FeI (mult. 44) lines pumped by the MgII emission (Refs. 21, 22) are observed in both α Tau and β Gru these lines are apparently not broad enough to pump FeII uv 32 or uv 373. Mult. uv 32 is present and its strength can be attributed to pumping by uv 1 which has an opacity of $\sim 10^3$. There is similar interlocking between the other multiplets observed. In β Gru uv 399, which terminates on the upper level of uv 63 is particularly strong, and the population of the upper and lower levels of uv 399 are comparable, indicating a selective population mechanism. It has been pointed out previously (Ref. 1) that H Ly α can excite levels in the 5p configuration of FeII, the classifications of which have been extended by Johansson (Ref. 23). These 5p levels can then decay to the 5s levels giving rise to uv 399 and similar multiplets. (Penston has privately pointed out the strength of uv 399 in RR Tel. and suggested recombination as a cause). Johansson found that charge exchange with NeII is important for FeI → FeII in laboratory sources. Since the FeII multiplets are important not only for stellar spectra but also for quasars and Seyfert galaxies it is of interest to investigate these possibililes further.

Finally, the possible role of H Ly α in photo-exciting (or effectively ionizing) high levels of SI is pointed out. The relative strengths of the SI 1425 and 1475 multiplets do not appear to be consistent with collisional excitation, using f-values and solar relative intensities as a guide to the cross-sections. The strong lines of SI observed ie. mult. uv 3, uv 2, uv 1, and uv 9 originate from the lowest terms formed by recombination from the three possible SII parents. The strength of the SI emission suggests a recombination or cascade spectrum following photo-ionization (or excitation) by radiation around H Ly β.

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Table 1

Spectra Obtained

Star	Type	Date	Exposure Time (min)	Resolution	Camera
α Tau	K5III	78/9/29	20	LO	SWP
		78/10/1	40	LO	SWP
		79/1/25	90	LO	SWP
		79/1/27	150	LO	SWP
		79/9/29	390	HI	SWP
		78/1/10	10	LO	LWR
		79/9/29	10	HI	LWR
β Gru	M2II	79/10/1	175	LO	SWP
		79/10/7	370	HI	SWP
		79/10/1	20	HI	LWR

Table 2

Opacity Sensitive Line Sets

Atom	Transition	Δ J	λ (A)
CI	$2p^2\ {}^3P-2p3s\ {}^3P°$	2-1	1658.1
		1-1	1657.4
		0-1	1657.9
	$2p^2\ {}^1D-2p3s\ {}^3P°$	2-1	1993.6
	$2p^2\ {}^3P-2p3s\ {}^1P°$	2-1	1614.5
		1-1	1613.8
		0-1	1613.4
	$2p^2\ {}^1D-2p3s\ {}^1P°$	2-1	1930.9
OI	$2p^4\ {}^3P-2p^33s\ {}^3S°$	2-1	1302.17
		1-1	1304.86
		0-1	1306.03
	$2p^4\ {}^1D-2p^33s\ {}^3S°$	2-1	1641.30
SI	$3p^4\ {}^3P-3p^34s"\ {}^3P°$	2-1	1296.17
		1-1	1302.87
	$3p^4\ {}^3P-3p^34s\ {}^3S°$	2-1	1807.34
		1-1	1820.36
		0-1	1826.26